

Advanced Flag-Shape Systems for High Seismic Performance including Near-fault Effects

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ABSTRACT: Experience with recent earthquakes near urban centers (Northridge 1994, Kobe 1995, Chi-Chi 1999) highlighted two major challenges in seismic engineering: the hazard and peculiarity of near-fault earthquakes, characterised by low number of cycles and high velocity pulses in its motion and the urgent need for performance-based design and retrofit approaches for buildings in near-fault urban centers such as Wellington City. Meanwhile, the development of high-performance seismic resistant hybrid systems or flag-shape systems, incorporating combination of re-centering elements and hysteretic energy dissipation, have shown to significantly reduce the expected level of damage when compared with traditional (i.e. monolithic) ductile systems. However, traditional hysteretic dissipation is considered inherently inadequate to counteract the near-fault effects. In this paper, the innovative concept of Advanced Flag-shape Systems (AFS) is proposed as an alternative solution for high-seismic performance system in near-fault regions. AFS combines alternative forms of energy dissipation (yielding, friction or viscous damping) in series and/or in parallel together with re-centering elements to achieve high seismic performance for both far-fault and near-fault motions. The concept of AFS is first briefly discussed qualitatively and then numerically investigated using SDOF models subjected to push-pull and time-history analyses under a suit of far field and near fault events. Finally, the enhanced performance of AFS systems is compared and discussed with monolithic solutions or more traditional Flag-shape systems.

1 INTRODUCTION

Lessons from the recent earthquakes (Northridge 1994, Kobe 1995, Chi-Chi 1999) highlighted the vulnerability of current buildings. This underscores the inadequacy of the traditional ductile design, which has been primarily focussed on collapse prevention, in limiting financial costs, in terms of repair, downtime and rehabilitation costs. Subsequently, with the introduction of the Performance-Based Earthquake Engineering (PBEE) (SEASOC 1995), emphasis has been given to minimizing damage and building downtime post-earthquake events. The concept of PBEE has also been extended to seismic retrofitting as stakeholders seek to achieve targeted performance levels especially in critical-use structures such as hospitals (fib 2003a). In line with development of PBEE, high-performance seismic resisting systems that are able to sustain major ground motions without substantial damage have been developed in the precast concrete industry. The developments of dissipation devices, subassembly connections and systems, termed as hybrid connections/systems, exhibiting a “flag-shape” behaviour, characterized by the combination of self-centering and dissipation capacity, allow significant reduction of the expected level of damage when compared to traditional monolithic systems (fib 2003b). Re-centering capacity, provided by un-bonded post-tensioned tendons, can limit the residual (post event) deformations to a negligible value (Pampanin et al. 2002). The flag-shape systems hence are able to achieve a non-damage performance level, even at high earthquake intensity.

However, post-Northridge research has highlighted the peculiarity of structural responses under near-source events, and the potential of using velocity-dependent (e.g viscous) damping to counter the effects. Traditionally, the use of viscous dissipation has been proposed as supplementary damping to an elastic structure as part of a passive or active structural control system (Soong and Dargush 1997).

However, in recent contributions (Kam et al. 2006), authors have proposed the concept of combining velocity-dependent and displacement-dependent (hysteretic or friction) dissipation, in parallel with a re-centering element, as advanced hybrid systems or, hereafter called as the Advanced Flag-shape Systems (AFS) or advanced hybrid systems as an alternative solution for high-seismic performance system in near-fault regions. The present paper addresses the challenge of further validating the concept of Advanced Flag-shape (AFS) systems with the emphasis on its superiority against near-fault effects. The conceptual development and key parameters in the design process of the AFS systems will be briefly summarised. Then, the enhanced seismic performance is demonstrated with a series of inelastic time history analysis using a suite of far field and near-field records. This paper represents part of the analytical work that belongs to a larger experimental-analytical investigation program for advanced seismic resisting system at the University of Canterbury.

2 NEAR-FAULT GROUND MOTIONS EFFECTS

The increased number of recorded ground motions from major earthquakes near urban centers in recent years demonstrates the hazard and peculiarity of the ground motions near the faults. Since the 1971 San Francisco earthquake, the peculiar structural response to near-fault ground motions has been documented. (Bertero et al. 1978; Somerville et al. 1997). The amplification of seismic waves in the direction of rupture due to forward directivity effect has lead to low-cycles motion with a coherent long period velocity pulse termed as “fling effect”. In some cases, acceleration histories recorded may contain random high frequency spikes, resembling traditional far-fault earthquakes, but their velocity and displacement histories have a coherent long-period pulse, as illustrated in Figure 1a. Near-fault motion has been shown to cause significant strength, displacement and ductility demand in structures as well as variation in inter-storey shear demand for both long and short period structures (Alavi and Krawinkler 2001; Hall et al. 1995; MacRae et al. 2001). More urgently, modern structures in near fault regions might have inadequate displacement or ductility capacities because near-fault effects are often overlooked or underestimated in design codes. Prior to the 1997 Uniform Building Code ((ICBO) 1997), there was no amplification of demand for near-fault effects in major building codes worldwide. Even in the recent Eurocode 8 (CEN 2006), there is no provision for near-fault effects in designing for buildings (Part 1), though there is a site-specific spectra requirement in design for bridges within the fault zone.(Part 2).

In the NZS1170:5 (2004), the near-fault amplification factor for elastic design spectra was based on a near-fault attenuation model that has been shown to be inconsistent when compared to recorded strong ground motion data (Somerville 2005). McVerry et al (2006) cited the lack of near-source records in the New Zealand strong-motion database for the lack of a calibrated attenuation model for spectra generation. Figure 1b shows the comparison between spectra velocity for four un-scaled near-fault records to the NZS 1170:5 (2004) elastic design spectra for the sites’ soil conditions and near fault amplification. The pulse period (period in which the spectral velocity peak) can vary significantly with some correlation with the magnitude of the earthquake. A preliminary magnitude-dependent response spectra model that is significantly different from existing models used in codes has also been recently proposed (Somerville 2005). In reality, the ongoing development with hazard spectra accounting for near-fault effect highlights the uncertainty and challenge of designing for near-fault regions.

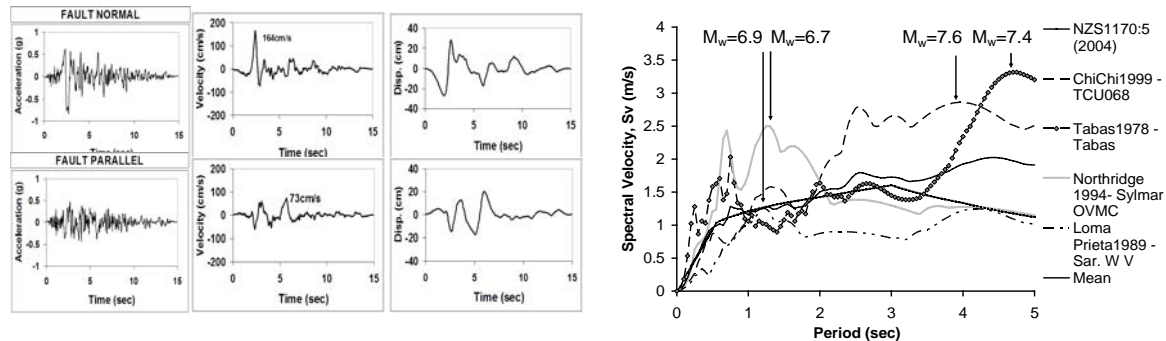


Figure 1: a) Rinaldi Station, Northridge 1994 ; b) Spectra Velocity for 4 Near fault Ground Motions

3 THE CONCEPTS OF ADVANCED FLAG-SHAPE (AFS) SYSTEMS

The following sections briefly describe the conceptual development of the Advanced Flag-Shape (AFS) systems starting from the traditional Flag-shape Systems. Further details of the development of the concept are available in (Kam et al. 2006).

3.1 Traditional Flag-shape Systems and Limitations

A traditional flag-shape or hybrid system combines the re-centering capability from the un-bonded post-tensioning tendons and the energy dissipating capability from additional energy dissipation hysteretic/yielding devices (either internal or external) to guarantee limited damage in structural elements by limiting residual displacements. The plastic deformation, traditionally carried in plastic hinges of a monolithic ductile connection, is accommodated at the section interface by the opening and closing of the joint under a “controlled rocking” motion. A design guideline for the application of flag-shape connections for precast concrete has also been published in the literature (NZS3101 2005). Subsequently, the concept has been extended to steel frame structures, bridge piers/systems and more recently LVL (laminated veneer lumber) timber multi-storey buildings. A comprehensive overview on the design and development of the traditional flag-shape systems can be found in Pampanin (2005).

Early flag-shape systems utilize hysteretic yielding dissipation in the form of internal or external mild steel elements and friction elements, hence relying purely on displacement-based hysteretic damping for energy dissipation (Priestley et al. 1999). While this solution may be effective in a typical far-field earthquake event, it is expected such a system may encounter lower-than-expected dissipation in low-cycle high velocity near-fault earthquake events, which then induces higher ductility demand and floor acceleration within the system. Traditional hysteretic damping (displacement-proportional), whose efficiency is associated with the development of a full cycle response should be, in general, considered inadequate, to counteract the ‘fling’ effect of a near-fault event. Hence, the use of velocity-proportional dissipation, combined in series or parallel with other sources of dissipation (friction, elasto-plastic) seems to be the best viable solution to counter the effect of near-fault motion.

As the next development of the flag-shape systems, various forms of energy dissipation such as yielding, viscous, viscoelastic, friction in parallel and/or in series are considered as possible combinations with re-centering capacity from unbonded post-tensioning. Kurama (2001) has suggested the use of supplementary friction or viscous dampers in parallel with unbonded post-tensioned shear walls. Palermo et al (2005) meanwhile proposed to combine in parallel the concept of unbonded post-tensioning with various forms of energy dissipation. Other researchers, alternatively, have investigated the possibility of using a combination in series of viscous and hysteretic dampers for base isolation (Makris and Chang 2000) and for steel frame braces (Kasai and Minato 2005). Kam et al (2006) numerically investigated various combinations of different energy dissipations in series or/and in parallel with the re-centering system, termed as Advanced Flag Shape (AFS) systems.

3.2 Advanced Flag Shape (AFS) – Concept and SDOF model

The innovative concept of Advanced Flag-Shape (AFS) or advanced hybrid systems is suggested as an alternative solution for a high-seismic performance system, particularly in near-fault regions. By combining alternative forms of energy dissipation (yielding, friction or viscous damping) in series and/or in parallel together with re-centering elements, AFS system can guarantee high seismic performance for both far-fault and near-fault motions. In the initial study of AFS (Kam et al. 2006), it was found that a re-centering element in parallel with velocity-proportional dissipation can significantly reduce the ductility demand while maintaining its re-centering capacity. While the addition of velocity-proportional dampers is effective in reducing the ductility response, a high velocity pulse in a near-fault earthquake may cause the dampers to induce high acceleration forces within the superstructure. This result is consistent with other studies relating to the use of viscous dampers in base isolation systems, in which high floor acceleration and inter-storey drift can be of issues (Kelly 1999).

Kam et al (2006) also proposed the combination of a viscous or viscoelastic dampers in series with a friction slip damper, similar to the visco-elasto-plastic (VEP) braces proposed and tested by Kasai and

Minato (2005) as shown in Figure 2, in parallel with the traditional flag-shape system (unbonded post-tensioning with hysteretic yielding dissipation). It is also noted that a VEP element can be replaced with highly non-linear viscous dampers. Figure 3 presents the schematic representation of the AFS model in terms of SDOF mass-spring system and the practical applications of AFS system for bridge-pier, structural walls and beam-column joints. In a moderate far-field event, the hysteretic dissipation and unbonded post-tensioning would achieve non-damage re-centering behaviour similar to traditional flag-shape. In a near-fault event, the viscous/viscoelastic element acts to induce velocity-dependent energy dissipation, while the friction slipping element limits the force and acceleration in the system.

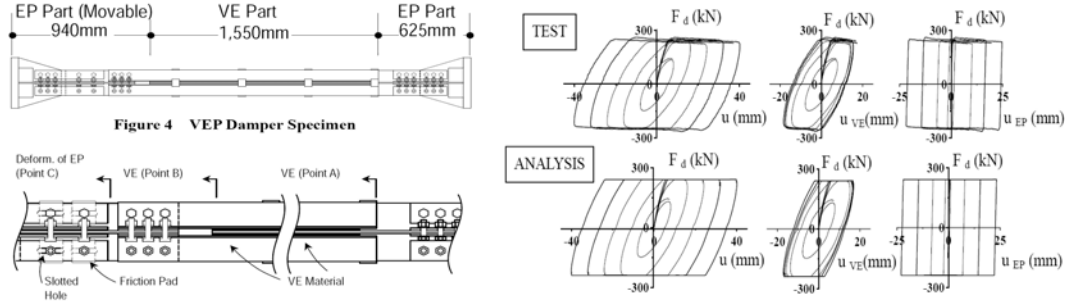


Figure 2: Visco-elasto-plastic damper proposed by Kasai and Minato (2005)

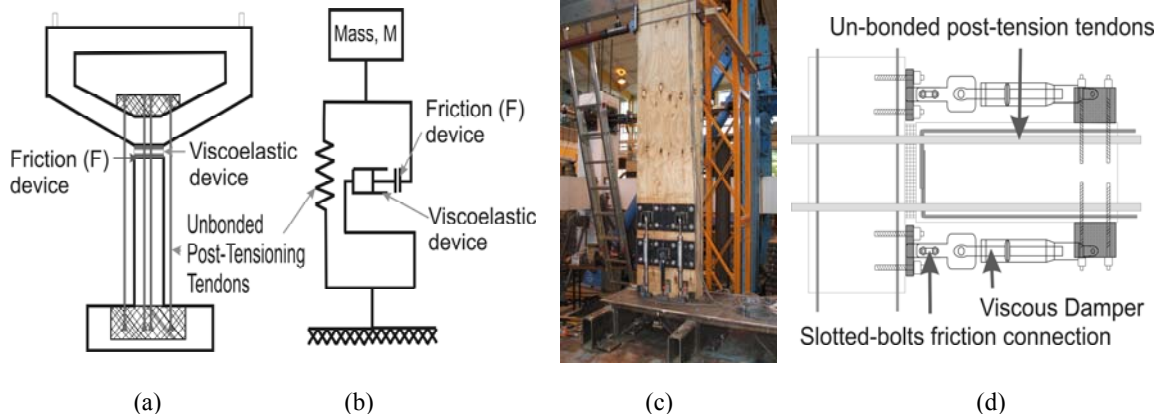


Figure 3: AFS: a) AFS Bridge Pier b) Schematic spring-mass SDOF model c) Experimental AFS Structural Wall (Marriott et al. 2007) d) Prototype of AFS Beam-column Joint

3.3 Governing Parameters

The design of a traditional flag-shape hybrid joint system is carried out by controlling the force or moment ratio of the self-centering contribution (unbonded post-tensioning) and the energy dissipation contribution (yielding elastoplastic or similar behaviour), here referred as λ_1 , as given by Equation 1. For traditional flag-shape systems, a fully self-centering capacity can, in principle, be guaranteed by assuming an appropriate force/moment contribution ratio, λ_1 (e.g. λ_1 has to be greater than the overstrength factor, α_0 in NZS3101(2005)). It is expected that a similar ratio as λ_1 would govern the self-centering capacity of advanced flag-shape systems.

$$\lambda_1 = \frac{M_{RE-CENTERING}}{M_{DISSIPATING}} \approx \frac{F_{RE-CENTERING}}{F_{YIELDING} + F_{VISCOUS}} \geq \alpha_0 \quad \text{where } \alpha_0 = \text{overstrength factor} \quad (1)$$

In addition to λ_1 , it is proposed that for AFS systems, which include both viscous and hysteretic components for energy dissipation, an additional force/moment design ratio, here referred as λ_2 —shown in Equation 2 and representing the ratio between the viscous, or velocity-dependent force/moment contribution, M_V , and the total dissipative force/moment, M_{TD} , is introduced as part of the design procedure. The λ_2 ratio controls the distribution of velocity-dependent and displacement-dependent dissipation contributions of the system. Therefore, by limiting it to a threshold value, the system can

be designed to avoid excessive force/acceleration in the system as well as achieve a targeted level of effective damping, ζ for the system. Parametric analysis of the two parameters is briefly presented in (Kam et al. 2006) and is currently under further investigation.

$$\lambda_2 = \frac{M_{\text{velocity-dependent-dissipation}}}{M_{\text{total-dissipation}}} \approx \frac{F_{\text{VISCOUS}}}{F_{\text{YIELDING}} + F_{\text{VISCOUS}}} \quad (2)$$

4 NUMERICAL INVESTIGATION ON SDOF RESPONSES

An extensive number of non-linear time history analyses were carried out to validate the concept proposed in this paper, and herein only a brief summary of the result are given along with one example for far field and near fault responses respectively. The inelastic time history analyses were carried out using the finite-element program RUAUMOKO2D (Carr 2006). A Rayleigh damping model proportional to the tangent stiffness was used with an initial viscous damping assumed to be 5% of the critical damping.

4.1 Hysteretic Models and Cyclic Push-Pull Calibration

Four hysteretic models were considered, representing four different ‘plastic-hinging’ mechanisms: a) the bi-linear elastoplastic model (EP), b) the flag-shape hysteresis model (FS), b) the non-linear elastic viscous model (NLEV), d) advanced flag-shape model (AFS). Figure 4a presents the schematic representation of the mass-spring SDOF models for each hysteretic model and their idealized force-displacement relationship. The SDOF models are calibrated to achieve a target monotonic force-displacement envelope under cyclic push-pull analysis, with effective period of 5.0 seconds and excitation velocity of 15cm/s (Fig. 4b). The equivalent viscous damping, ζ of each systems for target ductility of 4 are presented in Figure 4-c.

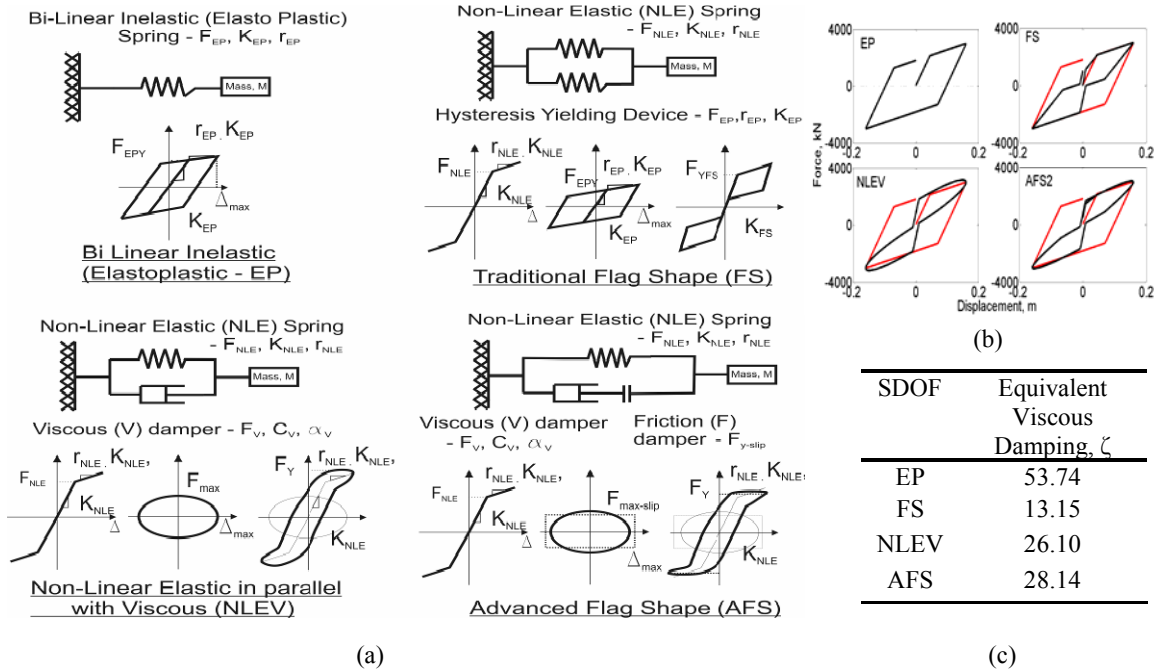


Figure 4: a) Idealized SDOF Models and Hysteretic Behaviour b) Force-displacement response of calibrated SDOF models c) Table of Equivalent Viscous Damping under Cyclic Push-pull

The bi-linear elastoplastic model (EP) is to represent monolithic reinforced concrete or steel structures. The model is chosen for its historical comparison as well as its simplicity. It is noted that no strength degradation is considered in this model, though in reality, monolithic structures may undergo significant degradation in their hysteretic behaviour. The flag-shape hysteretic model (FS) is a typical approximation of the traditional hybrid systems’ behaviour, experimentally and analytically proved in (Pampanin et al. 2001). The NLEV model is an improvement from the traditional flag-shape system,

in which viscous velocity-dependent dissipation is used instead of hysteretic dissipation. The AFS model is designed that velocity-dependent dissipation is 53% of the total dissipation (i.e. $\lambda_2 = 0.53$). All flag-shape systems and AFS have λ_1 of 1.21 to ensure self-centering.

4.2 Strong Ground Motion Records

Two suites of strong ground motion records were used, representing both far field and also near fault events. The elastic response spectra for both suites are shown in Figure 5. The first suite of earthquakes is an ensemble of 20 scaled historical ‘far-field’ strong ground motion records from California representative of typical earthquakes having a probability of exceedance of 10% in 50 years. These records were related to soil types C or D (NEHRP categories), with hypocentre depth ranging between 13 and 25km, and were generated by earthquakes of moment magnitude M_w ranging from 6.7 to 7.3. The adoption of the Californian earthquake set is for consistency with previous studies (Christopoulos et al. 2002).

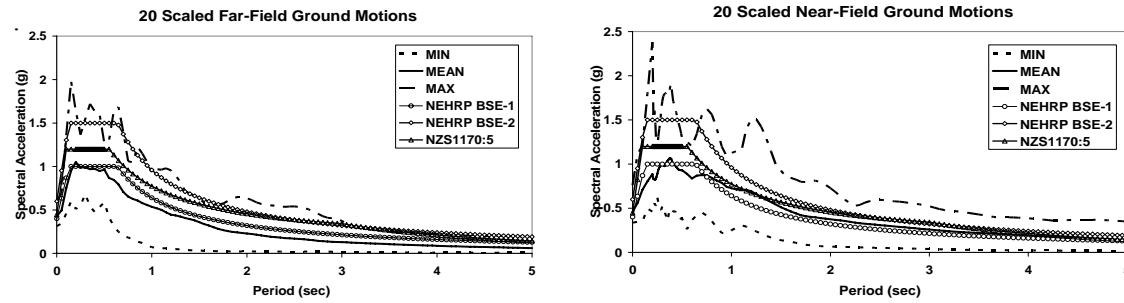


Figure 5: Elastic Acceleration Response Spectra: a) 20 Scaled Far-Field Ground Motions b) 20 Scaled Near-Fault Ground Motions

The second suite of earthquakes is an ensemble of 20 historical near-field earthquake records, selected based on its PGV/PGA ratio (at least 0.08 g s m⁻¹) and distance from fault (less than 10km). The source mechanism and soil type are selected such that a range of different properties are considered. Although the soft soil (type E) records typically exhibit large amplifications that are site-specific, the records are included in order to investigate the behaviour of AFS systems in all types of soil conditions. That is the same reason for selecting records with various source mechanisms. The suite of earthquake is then scaled to the NEHRP elastic spectra as with the first suite. The characteristics of the near-fault suite of records are presented in Table 1.

Table 1: Characteristics of the 20 Scaled Near-Fault Ground Motions (Fault Normal Direction)

Name	Earthquake Event	Year	Mw	Station	Rclosest (km)	Soil Type (NEHRP)	Source Mechanism	Scaling Factor	Scaled PGA (g)	Scaled PGV (cm/s)	Scaled PGV/PGA ratio
EQ21	Northridge	1994	6.7	Rinaldi Receiving Station	6.50	B	Reverse Normal	0.522	0.438	72.811	0.169
EQ22	Northridge	1994	6.7	Newhall Fire st.	5.92	D	Reverse Normal	0.625	0.369	35.826	0.099
EQ23	Northridge	1994	6.7	Sylmar - Olive view Med Ctr	5.30	D	Reverse Normal	0.643	0.542	70.200	0.132
EQ24	Northridge	1994	6.7	Los Angeles Dam	5.92	A	Reverse Normal	1.000	0.349	17.729	0.052
EQ25	Northridge	1994	6.7	Jensen Filter Plant	7.01	B	Reverse Normal	1.023	0.434	46.065	0.108
EQ26	Imperial Valley	1979	6.6	El Centro Array #5	3.95	D	Strike Slip	1.150	0.437	39.538	0.092
EQ27	Imperial Valley	1979	6.5	El Centro Array# 7	0.56	D	Strike Slip	1.184	0.548	59.910	0.111
EQ28	Kobe	1995	6.9	KJMA	1.00	B	Strike Slip	0.539	0.443	36.010	0.083
EQ29	Kobe	1995	6.9	Takatori	1.47	E	Strike Slip	0.609	0.372	47.246	0.130
EQ30	Kobe	1995	6.9	Port Island (0 m)	3.31	E	Strike Slip	1.070	0.337	25.231	0.076
EQ31	Kobe	1995	6.9	Kobe University	0.92	A	Strike Slip	1.590	0.461	25.273	0.056
EQ32	Loma Prieta	1989	6.9	Saratoga W Valley	9.31	D	Reverse Oblique	1.405	0.466	28.683	0.063
EQ33	Loma Prieta	1989	6.9	Los Gatos Pres Center	3.88	A	Reverse Oblique	0.620	0.349	33.115	0.097
EQ34	Chi Chi	1999	7.6	TCU068	9.96	D	Reverse Oblique	0.807	0.457	80.706	0.180
EQ35	Chi Chi	1999	7.6	CHY101	0.32	A	Reverse Oblique	0.981	0.432	49.659	0.117
EQ36	Kocaeli	1999	7.4	Gebze	10.92	A	Strike Slip	2.486	0.606	30.506	0.051
EQ37	Tabas, Iran	1978	7.35	Tabas	2	D	Reverse Normal	0.644	0.549	66.640	0.124
EQ38	Morgan Hill	1984	6.2	Coyote Lake Dam	0.1	A	Strike Slip	0.583	0.415	21.405	0.053
EQ39	San Fernando	1971	6.6	Pacoima Dam Abutment	1.81	A	Reverse Normal	0.620	0.760	85.550	0.115
EQ40	Landers	1992	7.3	Lucerne Valley	0.53	A	Strike Slip	0.641	0.462	45.103	0.099

4.3 Non-Linear Time History Responses Summary

Table 2 presents the summary of the responses of the time history analyses under far-field earthquake excitations. All the flag-shape systems (FS, NLEV and AFS) achieved negligible residual displacements, which imply minimal damage to the structures post-event, in comparison to the EP system. The results also confirm that flag-shape systems do not have higher peak response despite having lower “equivalent viscous damping ratio” (Fig. 4c). In an earthquake event, the EP typically

does not have sufficient large-displacement cycles to yield the higher energy dissipation implied by the equivalent viscous damping ratio. When comparing between NLEV and FS, it can be observed that the peak displacement responses are reduced (due to the velocity-dependent damping), but at a cost of higher peak forces. AFS in turn achieved superior performance from reduced peak displacement, zero residual displacement and peak force that are comparable to EP.

Table 3 presents the summary of the response of the time history analyses under near-fault earthquake excitations. Similar trends to the response under far-field types of excitation are, in general, observed in terms of reduced peak displacements as well as negligible residual displacements for flag-shape systems. In comparison between flag shape systems with (NLEV and AFS) and without viscous dampers (FS), significant peak responses reductions are achieved. However, the adverse effect of excessive force developed by the viscous damper contribution is more evident in the near fault events, in particular for NLEV, where the velocity-pulse, or fling effect, are significant. AFS however, managed to limit the peak forces within the system, as the friction slip coming into effect.

Table 2: Summary Far Field Earthquakes Inelastic Time History Analysis

Model	20 Far Field Earthquakes					
	Peak Force (kN)		Peak Displacement (mm)		Residual Displacement (mm)	
	Max	Mean	Max	Mean	Max	Mean
Bi-linear Elastoplastic (EP)	3844	2486	277.30	116.33	39.26	13.84
Traditional Flag Shape (FS)	3437	2528	220.40	114.88	5.01	1.21
Non-linear Elastic + Viscous (NLEV)	4057	2966	104.90	54.91	0.00	0.00
Advanced Flag Shape (AFS)	3522	2767	158.70	82.44	2.68	0.87

Table 3: Summary Near-Fault Earthquakes Non-linear elastic Time History Analysis

Model	20 Near Field Earthquakes					
	Peak Force (kN)		Peak Displacement (mm)		Residual Displacement (mm)	
	Max	Mean	Max	Mean	Max	Mean
Bi-linear Elastoplastic (EP)	4054	2962	305.30	172.14	51.91	16.55
Traditional Flag Shape (FS)	4290	3009	334.10	175.86	4.73	1.87
Non-linear Elastic + Viscous (NLEV)	5187	3512	140.10	80.22	0.00	0.00
Advanced Flag Shape (AFS)	4398	3177	243.10	128.89	3.44	1.21

The results presented in Table 2 and 3 clearly highlight the superior performance of AFS system regardless of the different characteristics of the input motions. As a clearer example, a comparison of the time-history response of the alternative seismic resisting systems for one near-fault and one far-field event are shown in Figure 8. The residual displacement of EP system is clearly evident for both near-fault and far-field motions. The high peak force from unconstrained NLEV system is more marked for the near-fault event. It is worth noting that the peak responses from near-fault events are generally more severe than those of far-field events, even for the same systems.

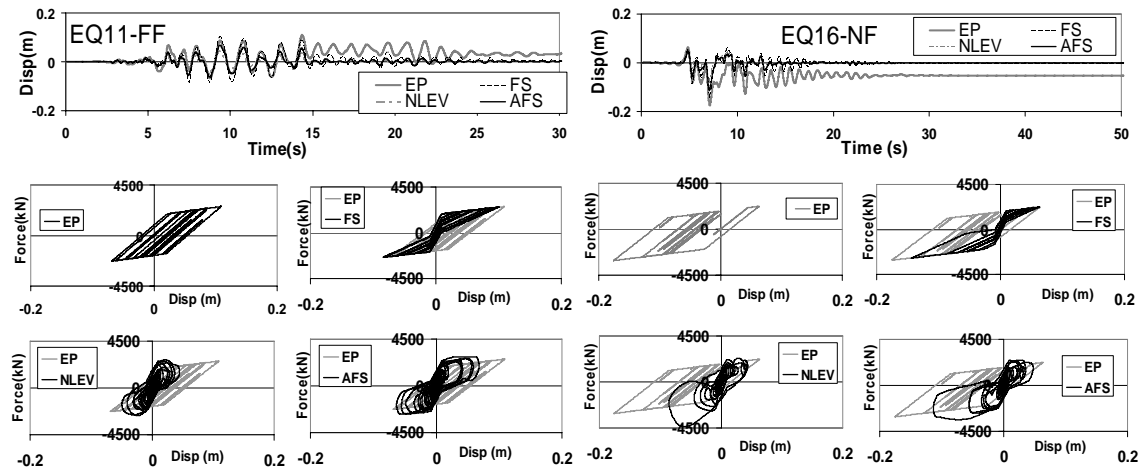


Figure 8: Inelastic Time History Plot for a) Far Field Earthquake for EQ11FF – Capitola, Loma Prieta 1989 (M=6.9, PGA =0.476g) b) Near-Fault Earthquake – EQ16NF: Gebze, Kocaeli, Turkey 1999 (M=7.4, PGA=0.606g)

CONCLUSIONS

The concept of Advanced Flag-shape (AFS) or advanced hybrid systems based on combination of alternative energy dissipations in series and/or in parallel with re-centering capacity is proposed. AFS is an improvement for the flag-shaped hybrid systems, specifically to account for near-fault effects, which are still largely overlooked. It is shown numerically that the AFS systems can reduce peak responses under both far field and near fault earthquakes while maintaining fundamental re-centering capability (negligible residual displacements). Peak forces within the system can be controlled by implementing a friction slipping element in series with a viscous damping contribution as in the AFS. More refined analytical investigations also extended to MDOF and experimental shake-table tests are on-going at the University of Canterbury, to confirm the viability of this second generation of hybrid flag-shape system.

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